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Pre-Development Distribution Patterns of Cesium-137, Uranium and Companion Elements in Lichen Heath Near Baker Lake N.W.T.

Summary of Findings
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Northern Affairs Program

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EXECUTIVE SUMMARY

The study was to establish the pre-development background levels of selected elements within the thalli of a number of arctic lichen species. Specimens were collected from permanent plots established on transects emanating from the Kiggavik (Lone Gull) site near Baker Lake.

Lichens are suitable plants for such a venture for a number of reasons: (1) they are ubiquitous at northern latitudes (2) they are valuable for monitoring the environment since they accumulate elements by trapping particulates (tiny dust particles), by anion uptake, by an extracellular cation-exchange process and (3) the collected lichen material can be archived in a suitable form for future reference, including analysis. Because of their sponge-like character, lichens are very susceptible to gaseous air pollutants, especially sulphur dioxide. Lichens have a considerable uptake capacity for metal ions due to the presence of metal-binding sites on both the algal and fungal parts.

Particle trapping is a second major mechanism by which lichens accumulate substances. Changes in the element ratios may be used as a parameter for monitoring the extent of fallout.

Lichens have been employed in various parts of the world to monitor environmental quality around smelters, manufacturing plants, power generating stations and urban centres, as well as around uranium mines. Reindeer Lichens have been used successfully to document fallout from global deposition associated with weapons testing.

SOMMAIRE

Cette étude visait à établir les niveaux de fond de certains éléments grâce à l'analyse du thalle de certaines espèces de lichens arctiques. Les spécimens ont été prélevés de sites permanents se trouvant sur des transects tracés à partir de l'emplacement Kiggavik (Lone Gull), non loin de Baker Lake.

Les lichens se prêtent aux études de ce genre pour plusieurs raisons : (1) on les trouve partout dans le Nord, (2) ils se prêtent bien aux études environnementales puisqu'ils accumulent les éléments chimiques (trois phénomènes : capture de poussières en suspension, absorption d'anions et échange extracellulaire de cations) et (3) les lichens prélevés peuvent être conservés à des fins de référence. Vu leur faculté d'absorption, les lichens sont très susceptibles aux polluants gazeux, notamment l'anhydride sulfureux. Enfin, ils possèdent une forte capacité d'absoption d'ions métalliques puisque leurs composantes algue et fongus comptent chacune des sites de liaison avec les métaux.

L'important mécanisme qu'est la capture des poussières en suspension donne au scientifique la possibilité d'étudier les proportions changeantes des différents éléments dans ces poussières, ce qui permet de contrôler les retombées de particules.

Dans différents pays, on a utilisé les lichens pour contrôler la qualité de l'environnement autour de fonderies, d'usines, de centrales électriques, de

centres urbains ainsi qu'aux environs de mines d'uranium. Le lichen des rennes, en particulier, a servi à documenter les retombées des essais d'armes nucléaires.

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TABLE OF CONTENTS

		Page
1.	RATIONALE FOR STUDY	3
2.	STUDY DESCRIPTION	6
	2.1 Introductory Remarks	6
	2.2 Field Work at Lone Gull, July-August, 1982	6
	2.3 Elemental Analyses	7
	2.4 Gamma-Ray Spectrometry	8
	2.5 Alpha-Particle Spectrometry	8
	2.6 Statistical Analysis of Data	8
	2.7 Scanning Electron Microscopy	9
3.	SUMMARY AND INTERPRETATION OF THE RESULTS	9
	3.1 Approach Taken to Reporting of Results	9
	3.2 Salient Features and Implications of the Findings	9
	3.2.1 Mean Concentrations of Seven Elements, % Ash and Cesium-137	9
	3.2.2 Transect-Dependent Distribution Patterns	10
	3.2.3 Inter-Element Correlations	11
	3.2.4 Element-To-Titanium Quotients	13
	3.2.5 Dependence of Mineral Accumulation on Species Morphology	13
	3.2.6 Uranium-238 and Thorium-232 Radioisotope Series	15
4.	RECOMMENDATIONS	15
5.	REFERENCES	16
	TABLES	22
	FIGURES	28

1. RATIONALE FOR STUDY

The intent of the 1982-84 ALUR-sponsored program (Arctic Land Use Research Program, Department of Indian and Northern Affairs Ottawa) was to establish the pre-development background levels of selected elements within the thalli of a number of arctic lichen species. Specimens were collected from permanent plots established on transects emanating from the uranium deposit at Lone Gull Lake near Baker Lake, N.W.T. Lichens are suitable plants for such a venture for a number of reasons: (1) these plants are ubiquitous at northern latitudes; (2) they are valuable for monitoring the environment since they accumulate elements by trapping particulates (tiny dust particles), by anion uptake, and by an extracellular cation-exchange process; and (3), the collected lichen material can be archived in a suitable form for future reference, including analysis.

Lichens are formed by an association of a fungus and an alga. The fungus, with a few exceptions, belongs to the cup-fungi group (Ascomycotina) while the alga may be bluegreen or green. The composite plant may be fruticose (shrubby), foliose (leafy), or crustose (crust-like). The algae in most lichens form a layer enclosed on both sides by fungal tissue which has no protective cuticle so that the water content of the whole lichen thallus rapidly equilibrates with the surrounding environment (Hale, 1983). Because of this sponge-like character, lichens are very susceptible to gaseous air pollutants, especially sulphur dioxide (Richardson and Nieboer, 1981; 1983a).

Lichens have a considerable uptake capacity for metal ions due to the presence of metal-binding sites on both the algal and fungal partners (Richardson and Nieboer, 1986b). Laboratory studies have shown that lichens exhibit ion-exchange ratios close to those expected for a synthetic ion-exchange resin (Nieboer and Richardson, 1981; Nieboer et al., 1976a,b). Particulate trapping is a second major mechanism by which lichens accumulate substances. Scanning-electron microscopic studies have shown that the surfaces of many lichens have numerous tiny holes through which particles of micron dimensions or larger can gain access to the interior, where they lodge among the less dense fungal strands of the medulla. It is often found in lichens from unpolluted areas, that the ratio of iron (Fe) to titanium (Ti) contents is rather constant due to the fact that Fe and Ti oxides tend to crystallize together during rock formation. Thus, if a lichen takes up tiny particles of rock, the ratio of the two elements will not alter much. However, around industrial plants emitting one or the other of these two elements, the value of such elemental-content ratio will change and this may be used as a parameter for monitoring the extent of fallout (Richardson and Nieboer, 1981; Boileau et al., 1982; Beckett et al., 1982; Nieboer et al., 1982). Similar relationships have been observed for other non-essential elements such as aluminum and scandium (Puckett and Finegan, 1980; Puckett, 1985).

Lichens have been employed in various parts of the world to monitor environmental quality around smelters, manufacturing plants, power generating stations, and urban centres (Nieboer and Richardson, 1981 Richardson and Nieboer, 1981; Gailey and Lloyd, 1986). Included among such studies has been the monitoring of the environment in and

around uranium mines (Boileau et al., 1982; Beckett et al., 1982; Nieboer et al., 1982). Normally, the elemental contents of a number of suitable lichen species are assessed as a function of distance from an identifiable emission source. The effective pollution zone may be inferred from the distance along transects where the elemental contents of these plants reach background values (Beckett et al., 1982). This approach is applied in the present study to an area in the Canadian arctic characterized by surface uranium deposits. This survey provides a measure of the background distribution in lichens of uranium and companion elements prior to developments such as mining. Data of this type are crucial since those living or working near uranium mines and refineries will demand assurances as to the adequacy with which their environments are monitored and protected. This is especially important because the radiation derived from uranium decay products is known to cause harmful effects such as radon-induced lung cancer.

And finally, reindeer lichens have been employed successfully to assess the global deposition of radionuclides derived from aerial nuclear-weapons testing and from atmospheric re-entry of nuclear powered satellites (Richardson and Nieboer, 1981). Cesium-137 contents will therefore be assessed in the current study to determine the current distribution of this anthropogenic fission product in arctic lichens.

2. STUDY DESCRIPTION

2.1 Introductory Remarks

The intent of this research was to establish the background levels of selected elements within the thalli of a number of lichen species, located in permanent plots established on transects radiating from the uranium deposit at Lone Gull Lake near Baker Lake, N.W.T. (64°18'N, 96°3'W) prior to any mining activity. At the same time, the analytical technology was selected and developed in such a way as to enable subsequent continuous monitoring of lichen samples if and when mining operations commence. Equally, the development of this program has been structured so that it is applicable for the monitoring of other potential arctic mining or industrial operations across Canada.

2.2 Field Work at Lone Gull, July-August, 1982

A field camp was located slightly remote and north of the main Urangesellschaft mining camp. Using the main camp as the focal point, four transects running approximately N, S, E and W were established; with sample plots located at 0.5, 1, 2, 4, 8 and 12 km along the east-west transects, and at 0.5, 1, 2, 4, 8, 16 km along the north-south transects, with an additional plot at 32 km on the southern transect. Since the prevailing wind is from the north and north-west it is anticipated that major particulate fallout will be in a southerly direction, and the design of the sampling layout reflects this (Fig. 1). Each permanent plot is approximately 100 x 100 m.

Following a general survey of the more common lichen species in the area, *Dactylina arctica*, *Cetraria cucullata*, and *C. nivalis* were chosen as representative of the local vegetation as a whole but also

representative of arctic Canada in general. Approximately 30 g of each species was collected from each permanent plot, labelled and returned to the laboratories at McMaster. Following careful hand sorting and washing, the dried lichen material was powdered with the aid of liquid nitrogen, and 2-g quantities of sieved material (70 mesh) were mixed with 0.5 g of Hoechst "C" wax and were subsequently compressed into pellets of 32 mm diameter and 2-3 mm thickness for elemental analysis. Pellets were made using a semi-automatic hydraulic press and applying a pressure of 12 tonnes for 1 min.

2.3 Elemental Analyses

The analyses of the plant tissues for Ti, Fe, Cu, Ni, Pb, S, Ca and K were achieved by X-ray fluorescence spectrometry (XRF) using the approach employed in earlier studies (Tomassini et al., 1976; Boileau et al., 1982; Beckett et al., 1982). The preparative work for the uranium analysis involved ashing 5 g of powdered lichen material in a programmable furnace (1 h at 150°C; 2 h, 250°C; 1 h, 350°C; 20 h, 500°C). The uranium analyses were carried out by employing delayed neutron counting (Ernst and Hoffman, 1982), where delayed neutrons are emitted from induced fission of, principally, ^{235}U. Samples (30-100 mg of ash) were irradiated in plastic vials for 60 s at a thermal neutron flux of $5 \times 10^{2} n\ cm^{-2} s^{-1}$, and were counted for 60 s after a 10-s delay. A detection limit of 0.03 µg of U is possible for this technique. Appropriate inter-method checks of representative standard and actual samples for the selected elements employed electrothermal atomic absorption spectrometry.

2.4 Gamma-Ray Spectrometry

Cs was determined using from 6 to 12 g of previously dried and ground lichen material placed in a 25 ml vial and analyzed using a GeLi detector supported by a PDP11/20 multichannel analyzer. Each sample was counted for 15 h. The resulting spectrum was recorded on magnetic tape or floppy disc and subsequently compared to that for the empty vial. No isotopes derived from the decay of ^{238}U or ^{232}Th could be detected in the samples.

2.5 Alpha-Particle Spectrometry

An α-particle spectrometer was assembled and calibrated as described in Kershaw et al. (1984). Other than recovery of uranium from standard samples, the electrodeposition/α-spectrometric method developed could not be applied to quantitative analysis of lichen samples. The detection limit of 1 µg of ^{238}U did not permit the determination of this α-emitter and others (e.g. ^{232}Th) in the lichens collected in the present study. However, these radioisotopes can be determined in lichen samples collected near uranium mining and milling operations (Kershaw et al., 1983).

2.6 Statistical Analysis of Data

Pearson's linear correlation coefficient statistic (r) and scatter diagrams were assessed using modified programs of the Social Sciences Statistical Package of the University of Pittsburg (Nie et al., 1975). In addition, the combined elemental content data for all three lichen species were explored for meaningful patterns of relationships using detrended correspondence analysis (DCA, Cornell University Multivariate Analysis Package; Hill, 1979). Currently, DCA

is the most successful and efficient multivariate analysis technique available, and is useful at revealing gradients or relationships within a data set (Hill and Gauch, 1980; Gauch, 1982). DCA was designed primarily as a technique for investigating vegetation distribution data, but is also eminently suitable for the identification of relationships among elemental distributions such as in soils and vegetation.

2.7 Scanning Electron Microscopy

Sputter-coated (Au) surface and cross sections of all three species were examined for morphological differences.

3. SUMMARY AND INTERPRETATION OF THE RESULTS

3.1 Approach Taken to Reporting of Results

The ALUR-supported research resulted in two publications (Looney et al., 1985, 1986) and a complete listing of the raw data and its detailed analysis are summarized in the March 1983 (Kershaw et al., 1983) and March 1984 (Kershaw et al., 1984) reports to ALUR. All four documents are deposited with the Department of Indian and Northern Affairs Ottawa. Only the highlights of the findings are reproduced in the present overview. The raw data is given in the appendix.

3.2 Salient Features and Implications of the Findings

3.2.1 Mean Concentrations of Seven Elements, % Ash and Cesium-137

The means and standard deviations for the elemental and ash contents by lichen species are summarized in Table 1. The observed levels in Cetraria nivalis and C. cucullata of Fe, Ti, S, Pb, Ca, K and Ni are comparable to those previously reported for the same lichen

species from the Mackenzie Valley, N.W.T., although the highest values do suggest some contribution from a mineral enriched substratum (Tomassini et al., 1976; Nieboer et al., 1978; Puckett and Finegan, 1980). The Cu concentrations appear characteristic for arctic sites without mineralization of the substratum but with some selective uptake. Comparable elemental data for Dactylina arctica are less available (see Tomassini et al., 1976), although it is evident from the data reported here that this species is a less efficient accumulator than the genus Cetraria. The low levels of U found in the three lichen species are in good agreement with other reported natural background concentrations of this metal (see Beckett et al., 1982, for review). The data indicate that the ^{137}Cs accumulation in lichens in Canada is similar to that found in Finland (Svoboda and Taylor, 1979; Taylor et al., 1979; Nieboer and Richardson, 1981). The ash contents are also typical of lichens from non-polluted environments (Nieboer et al., 1982). The data in Table 1 illustrate that Dactylina arctica has considerably lower ash, Ca, Fe and Ti contents than the two Cetraria species.

3.2.2 Transect-Dependent Distribution Patterns

It is obvious from the data in Figures 2 to 7 that the dependence of the elemental contents on distance along the transects was characteristic of the transect, the lichen and the element. In fact detrended correspondence analysis (DCA) showed that no consistent distribution pattern exists for the elemental contents with respect to dependence on distance (of collection site along the transect) or transect (whether the collection site was on the N, S,E or W transect) (Kershaw et al.,1984). Sulphur and potassium exhibited similar

distance- and transect- dependent distribution patterns (Figs. 2 and 5) as did Fe, Ti, U and ^{137}Cs (Figs. 3 to 5). Calcium and % ash distribution also resembled each other (Figs. 6 and 7). Because of these similarities, inter-elemental correlations must exist. As indicated, uranium grouped with Fe, Ti and ^{137}Cs, and thus no simple relationship with distance along the designated transects could be discerned. The data in Figures 2 to 7 reaffirm the previous observation that Dactylina arctica contained less Ca, Fe, Ti and ash than the two Cetraria species.

3.2.3 Inter-Element Correlations

All correlations (Tables 2 to 5) have been interpreted with consultation of scatter diagrams. Several significant correlations were indeed invalidated by outlier points. A selection of the observed linear correlations are shown in Figures 8 to 11.

There are very pronounced positive correlations between ash and Ca contents, between K and S, and for Fe, Ti and U. ^{137}Cs is also strongly correlated with Fe and Ti. The thallus concentrations of K and S are best interpreted as reflecting physiological parameters or status. The correlation between Fe and Ti has been shown to result from their occurrence together in particulates trapped in lichen thalli (Nieboer et al., 1978, 1982). (The data reported here further substantiated this conclusion; see Kershaw et al., 1983 for elaboration.) Further, it is concluded that since U is also strongly correlated with Fe and adsorption of ^{137}Cs on trapped particulates, and thus its grouping with Fe, Ti and U, is explained below.

Nuclear fallout of ^{137}Cs, and more recently that from the crashing of nuclear-powered satellites, presumably is particulate. Although ^{137}Cs has a short isotope half-life (30.1 y), its presence in lichen

samples collected in the N.W.T. and other parts of Canada as recently as 1978 remains well above the detection limit of gamma-ray spectrometry. Particulates of minerals such as metal oxides, hydrous oxides, metal sulphides and clays are often charged, especially when moistened (Stumm and Morgan, 1981). In fact, the solid-solution interfaces and the associated colloidal properties provide a vehicle for physicochemical interactions that have important ecological repercussions. Forces acting at interfaces are extensions of forces acting within the two separate phases. Surface adsorption of ions, of organic molecules and no doubt of small particulates, by inorganic particulate matter is a known phenomena, and is the subject of intense study (Stumm and Morgan, 1981). We propose therefore, on the basis of the strong association of ^{137}Cs with Fe, Ti and U, that this radioisotope is adsorbed either as the ion or very small particulates onto inorganic dust, which, of course, is available for trapping by lichens. To our knowledge, this mode of distribution of radioisotopes resulting from nuclear fallout has not been recognized previously.

The data show a negative correlation between Ca (or % ash) and Fe or Ti (Tables 2-5; Fig. 11). Interestingly, Erdman et al. (1977) reported a strong positive correlation between Ca and % ash, but a strong negative association for silicon and ash, and aluminum and ash. In this study Ca was also found to be the main contributor to the non-combustible, inorganic ash (Fig. 10). X-ray diffraction studies by Erdman et al. (1977) revealed that Ca was present as calcium oxalate in the intact lichen thallus and as calcium carbonate (calcite) in the ash. Mass balance calculations for our own data do indeed indicate that Ca is the primary lichen constituent contributing to the incombustible ash. Collectively, these observations suggest that

calcium-rich lichen thalli appear to exclude exogenous dust particulates, perhaps because calcium oxalate of endogenous origin fills the extracellular interstitial spaces.

3.2.4 Element-To-Titanium Quotients

In Table 6, a comparison is made of the element-to-titanium quotients observed in the three lichen species with those reported for the four main rock types found in the study area. It is evident from the good agreement for both the Fe/Ti and U/Ti content ratios that dirty quartzite most closely resembles the composition of the particulates trapped in the lichens (Fig. 12). Perhaps this rock type weathers readily, and the resulting particulates are distributed across the study area by wind and surface-water runoff. As expected, the content ratios Ca/Ti and K/Ti are elevated in the lichens, and do reflect the physiological need for Ca, Cu and K by these plants (Puckett and Finegan, 1980). While the data for Ni is equivocal, the enhancement of the Pb/Ti ratio in the three lichen species would appear to be consistent with the known global lead fallout from automobile and related emissions (Nieboer et al., 1978).

3.2.5 Dependence of Mineral Accumulation on Species Morphology

The magnitude of the Fe/Ti content ratios is clearly characteristic of a lichen species (Table 6). In addition, lichens also differ in their percent inorganic ash content (Table 1). On average, the Cetraria species contained about twice as much incombustible ash than Dactylina arctica. Although genus and species dependent, ash levels of 1-2% are typical of fruticose lichens growing in clear air environments (Lounamaa, 1965). In this situation, the

macronutrients Ca, Mg, K, Na and S, and perhaps Fe, are expected to contribute the largest share since the observed concentrations of trace elements such as of Ti, Cu, Pb and Ni, even when trapped as particulates, would add only in a minor way to the total (Nieboer et al., 1982). This interpretation, draws support from the lack of association between the observed elemental contents (except Ca) and the percent ash (Table 2 to 5).

It is evident that the elemental content differences between Dactylina arctica and the two Cetraria species reflect markedly different abilities to trap particulates in the lichen thallus. This difference is very clearly shown in the ordination of lichen samples using detrended correspondence analysis, DCA (Kershaw et al., 1984; Looney et al., 1985). The samples of Dactylina arctica, with one exception, have very low loadings on the first DCA-ordination axis which is characterized by high % ash and Ca contents. The average iron-to-titanium content quotients were also considerably higher for this lichen (Table 6). Since composition is known to vary with the size of particulates (see Nieboer et al., 1982), this observation suggests differential trapping according to size. Scanning electron microscopic studies of individual thalli of the three species exhibit very contrasting surface irregularities together with quite different internal organization, including differences in the prominence and size of interstitial spaces (Kershaw et al., 1984; Looney et al., 1985, 1986). These distinct features agree well with the apparently contrasting particulate trapping abilities of Dactylina to the Cetraria species.

3.2.6 Uranium-238 and Thorium-232 Radioisotope Series

The detection limit of about 1 µg ^{238}U was not sensitive enough to permit the determination of this α-emitter and other members of the ^{238}U and ^{232}Th series in the Baker Lake lichen samples. However, as reported in Kershaw et al. (1983), these α-emitting radioisotopes have been determined by electrodeposition/α-spectrometry in lichen and moss specimens collected near the Elliot Lake (Ontario) uranium mining and milling operations.

4. RECOMMENDATIONS

4.1 Contingent on the initiation of any active mining at the Lone Gull Lake, N.W.T. site, appropriate samples (30 g dry wt.) preferably of Cetraria nivalis, but if unavailable of C. cucullata or Dactylina arctica, should be collected at time intervals from each permanent plot established in the current work.

4.2 These samples should be processed and analyzed as outlined in the reports deposited with the Department of Indian and Northern Affairs Ottawa (Kershaw et al., 1983,1984), and the data obtained compared sequentially with the baseline values reported to assess accurately:

a) iron and titanium contents and the corresponding Fe/Ti content quotients as an estimate of particulate emissions;

b) total uranium and perhaps nickel and lead, or other elements diagnostic of the ore body, to determine the degree of dispersion of these potentially toxic metals;

c) gamma-ray and alpha-particle spectra of representative lichen samples to assess concentration changes and the dispersion of radioisotopes derived from the radioactive decay of uranium-238 and thorium-232. Cesium-137 measurement should reveal any changes in atmospheric fallout pattern of this anthropogenic nuclear-fission product.

4.3 Prior to the initiation of any other Canadian arctic uranium mining activity, it is recommended that similar permanent plots be established to allow continuous monitoring of any particulate emission from the subsequent mining operation.

4.4 Research should be initiated to determine the vertical mobility and fluxes of ionic forms of uranium and associated metals in lichens. The extent that lichens are able to weather and break down trapped particulates, and thus to mobilize toxic elements, is also in need of study. Work of this nature would enable realistic guidelines to be established for mining operations and would permit an assessment to be made of the total ecological impact, including any toxicological effects on man *via* the lichen-caribou food chain as well as by direct exposure.

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TABLE 1: The means and standard deviations for the results of the lichen analyses by species. Also shown are the F-values indicating significant differences between means. Values are based on n = 25 for each species except Cs†, and are expressed per air-dry weight.

Species		Ash %	Ca $\mu g g^{-1}$	Cs $nCi Kg^{-1}$	Cu $\mu g g^{-1}$	Fe $\mu g g^{-1}$	K $\mu g g^{-1}$	Ni $\mu g g^{-1}$	Pb $\mu g g^{-1}$	S $\mu g g^{-1}$	Ti $\mu g g^{-1}$	U $\mu g g^{-1}$
Cetraria cucullata	$\bar{X}$	1.66	4380	4.33	3.05	88.9	1460	1.99	3.76	302	13.49	0.020
	s	(0.51)	(2300)	(1.64)	(1.56)	(35.5)	(475)	(0.81)	(1.39)	(69)	(4.53)	(0.018)
Cetraria nivalis	$\bar{X}$	2.06	7970	5.00	2.92	74.0	1250	1.83	4.49	263	12.73	0.018
	s	(0.61)	(3860)	(2.86)	(4.10)	(50.2)	(366)	(1.11)	(2.90)	(73)	(8.62)	(0.010)
Dactylina arctica	$\bar{X}$	0.89	2100	3.73	3.88	41.5	1380	1.67	5.52	254	4.60	0.013
	s	(0.18)	(860)	(1.80)	(1.50)	(14.5)	(450)	(0.63)	(3.09)	(48)	(1.43)	(0.006)
	F∞	40.88 ***	31.46 ***	1.64	0.94	11.05 ***	1.51	0.86	2.99	3.99 *	18.80 ***	2.19

† For Cs: Cetraria cucullata, n = 17; Cetraria nivalis, n = 21; Dactylina arctica, n = 19.

∞ F test for difference between means: *, $p < 0.05$; ***, $p < 0.001$.

TABLE 2: Pearson's (r) correlation coefficients as determined for *Cetraria cucullata*, *C. nivalis* and *Dactylina arctica* combined for all locations, for the elemental concentrations (per air-dry weight) and the % Ash content. n = 75 except for Cs where n = 57.

	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
% Ash	0.8528 (.000) ***	0.0207 (.439)	-0.0762 (.258)	0.1636 (.080)	-0.0876 (.227)	0.0736 (.256)	-0.1541 (.093)	0.1920 (.049) *	0.2640 (.011) *	0.2316 (.023) *
Ca		0.0111 (.467)	0.0184 (.438)	-0.0774 (.255)	-0.2161 (.031) *	0.0449 (.351)	-0.1007 (.195)	0.0724 (.269)	0.0509 (.332)	0.0874 (.228)
Cs			0.0982 (.234)	0.5368 (.000) ***	-0.0192 (.444)	0.4134 (.001) ***	0.4335 (.000) ***	-0.0335 (.402)	0.5396 (.000) ***	0.3276 (.006) **
Cu				-0.0390 (.370)	-0.0614 (.300)	0.0935 (.213)	0.2490 (.016) *	-0.1506 (.099)	-0.0301 (.399)	0.1041 (.187)
Fe					0.1730 (.069)	0.2379 (.020) *	0.1012 (.194)	0.2414 (.018) *	0.9632 (.000) ***	0.4874 (.000) ***
K						-0.1210 (.151)	-0.1690 (.074)	0.8479 (.000) ***	0.1068 (.181)	0.2376 (.020) *
Ni							0.2566 (.013) *	-0.1446 (.108)	0.1949 (.047) *	0.1023 (.191)
Pb								-0.2675 (.010) **	0.0719 (.270)	0.0161 (.445)
S									0.2095 (.036) *	0.2713 (.009) **
Ti										0.4470 (.000) ***

One-tailed probability values are given in parentheses beneath the correlation coefficient: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

TABLE 3: Pearson's (r) correlation coefficients as determined for Cetraria cucullata for all locations, for the elemental concentrations (per air-dry weight) and the % Ash content. n = 25 except for Cs where n = 17.

	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
% Ash	0.9124 (.000) ***	-0.4666 (.030) *	-0.1644 (.216)	-0.0538 (.399)	-0.1480 (.240)	-0.3545 (.041) *	-0.0055 (.490)	0.0994 (.318)	-0.0087 (.484)	-0.1244 (.277)
Ca		-0.5193 (.016) *	-0.2445 (.119)	-0.2614 (.103)	-0.3705 (.034)	-0.1884 (.184)	0.0531 (.401)	-0.1700 (.208)	-0.2233 (.142)	-0.2086 (.159)
Cs			0.0749 (.388)	0.2923 (.127)	0.3590 (.079)	-0.0391 (.441)	-0.0061 (.941)	0.3025 (.119)	0.2823 (.136)	0.2218 (.196)
Cu				0.4572 (.011) *	0.3581 (.039) *	0.3104 (.066)	0.0900 (.334)	0.3414 (.047) *	0.4382 (.014) *	0.5731 (.001) ***
Fe					0.4180 (.019) *	-0.0204 (.461)	0.0161 (.469)	0.4363 (.015) *	0.9783 (.000) ***	0.4954 (.006) **
K						-0.0234 (.456)	0.1238 (.278)	0.9174 (.000) ***	0.4067 (.022) *	0.3781 (.031) *
Ni							0.4125 (.020) *	-0.1110 (.299)	-0.0805 (.351)	-0.0739 (.363)
Pb								-0.0031 (.494)	-0.0155 (.471)	-0.0865 (.341)
S									0.4336 (.015) *	0.3599 (.039) *
Ti										0.5018 (.005) **

One-tailed probability values are given in parentheses beneath the correlation coefficient: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

TABLE 4: Pearson's (r) correlation coefficients as determined for Cetraria nivalis for all locations, for the elemental concentrations (per air-dry weight) and the % Ash content. n = 25 except for Cs where n = 21.

	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
% Ash	0.6946 (.000) ***	-0.1533 (.254)	0.1548 (.230)	-0.2844 (.084)	-0.0044 (.492)	0.2208 (.144)	-0.0167 (.468)	0.1931 (.178)	-0.3359 (.050) *	0.4535 (.011) *
Ca		-0.1169 (.307)	0.2714 (.095)	-0.4871 (.007) **	-0.0103 (.481)	0.0926 (.330)	-0.0638 (.381)	0.2682 (.097)	-0.4805 (.008) **	0.1336 (.262)
Cs			0.3994 (.036) *	0.6964 (.000) ***	-0.2035 (.118)	0.4353 (.024) *	0.5678 (.004) **	-0.1492 (.259)	0.6758 (.000) ***	0.6653 (.000) ***
Cu				-0.0735 (.364)	-0.3577 (.040) *	0.0802 (.352)	0.2658 (.100)	-0.3507 (.043) *	0.0130 (.475)	-0.0169 (.468)
Fe					0.0185 (.465)	0.3135 (.064)	0.5285 (.003) **	-0.0458 (.414)	0.9848 (.000) ***	0.5049 (.005) **
K						-0.2863 (.083)	-0.3085 (.067)	0.8865 (.000) ***	0.0212 (.460)	-0.0995 (.318)
Ni							0.3836 (.029) *	-0.2856 (.083)	0.2439 (.120)	0.3710 (.034) *
Pb								-0.2456 (.118)	0.5290 (.003) **	0.3789 (.031) *
S									-0.0430 (.419)	-0.0072 (.486)
Ti										0.4466 (.013) *

One-tailed probability values are given in parentheses beneath the correlation coefficient: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

TABLE 5: Pearson's (r) correlation coefficients as determined for Dactylina arctica for all locations, for the elemental concentrations (per air-dry weight) and the % Ash content. n = 25 except for Cs where n = 19.

	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
% Ash	0.7325 (.000) ***	-0.2877 (.116)	-0.1661 (.214)	-0.1203 (.283)	0.2948 (.076)	-0.0082 (.484)	-0.0328 (.438)	0.4230 (.018) *	-0.1350 (.260)	0.4420 (.013) *
Ca		-0.4025 (.044) *	-0.0762 (.359)	-0.3693 (.035) *	-0.3451 (.046) *	-0.0181 (.466)	0.0843 (.344)	-0.0709 (.368)	-0.4076 (.022) *	0.0551 (.397)
Cs			0.2719 (.130)	0.3636 (.063)	0.0302 (.451)	0.6893 (.001) ***	0.4926 (.016) *	-0.1756 (.236)	0,3022 (.104)	-0.1703 (.243)
Cu				0.0121 (.477)	0.0242 (.454)	0.0581 (.391)	0.2709 (.095)	-0.0028 (.495)	-0.0261 (.451)	-0.0925 (.330)
Fe					0.2202 (.145)	0.1463 (.243)	0.0196 (.463)	0.0626 (.383)	0.9256 (.000) ***	0.2049 (.163)
K						-0.0989 (.319)	-0.2202 (.145)	0.8681 (.000) ***	0.2458 (.118)	0.4587 (.011) *
Ni							0.2166 (.149)	-0.1555 (.229)	0.0733 (.364)	-0.2552 (.109)
Pb								-0.3412 (.048) *	-0.1108 (.299)	-0.0521 (.402)
S									0.0769 (.357)	0.4121 (.020) *
Ti										0.2518 (.112)

One-tailed probability values are given in parentheses beneath the correlation coefficient: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

TABLE 6: Quotients of selected metals to Ti based upon lichen/lichen or rock/rock values. Lichen values are from this study, n = 25 for each species. Geology values were calculated from analytical results from Urangesellschaft, Canada Limited.

Species or Rock Type		Ca/Ti	Cu/Ti	Fe/Ti	K/Ti	Ni/Ti	Pb/Ti	U/Ti
Cetraria cucullata	$\bar{X}$	368	0.234	6.53	115	0.161	0.302	0.0014
	s	(259)	(0.135)	(0.54)	(46)	(0.082)	(0.137)	(0.0008)
Cetraria nivalis	$\bar{X}$	1090	0.313	5.80	153	0.197	0.402	0.0018
	s	(1140)	(0.517)	(0.91)	(117)	(0.142)	(0.202)	(0.0015)
Dactylina arctica	$\bar{X}$	524	0.921	9.02	318	0.392	1.319	0.0029
	s	(322)	(0.474)	(1.00)	(118)	(0.201)	(0.871)	(0.0015)
Dirty-Quartzite		0.80	0.007	6.38	13.63	0.0003	0.011	0.0022
Ortho-Quartzite		1.19	0.042	34.95	41.50	0.2500	0.042	0.0083
Granite		6.70	0.004	9.92	42.21	0.0009	0.089	0.0625
Thelon Sandstone		0.12	0.004	30.63	3.12	0.0142	0.004	0.0026

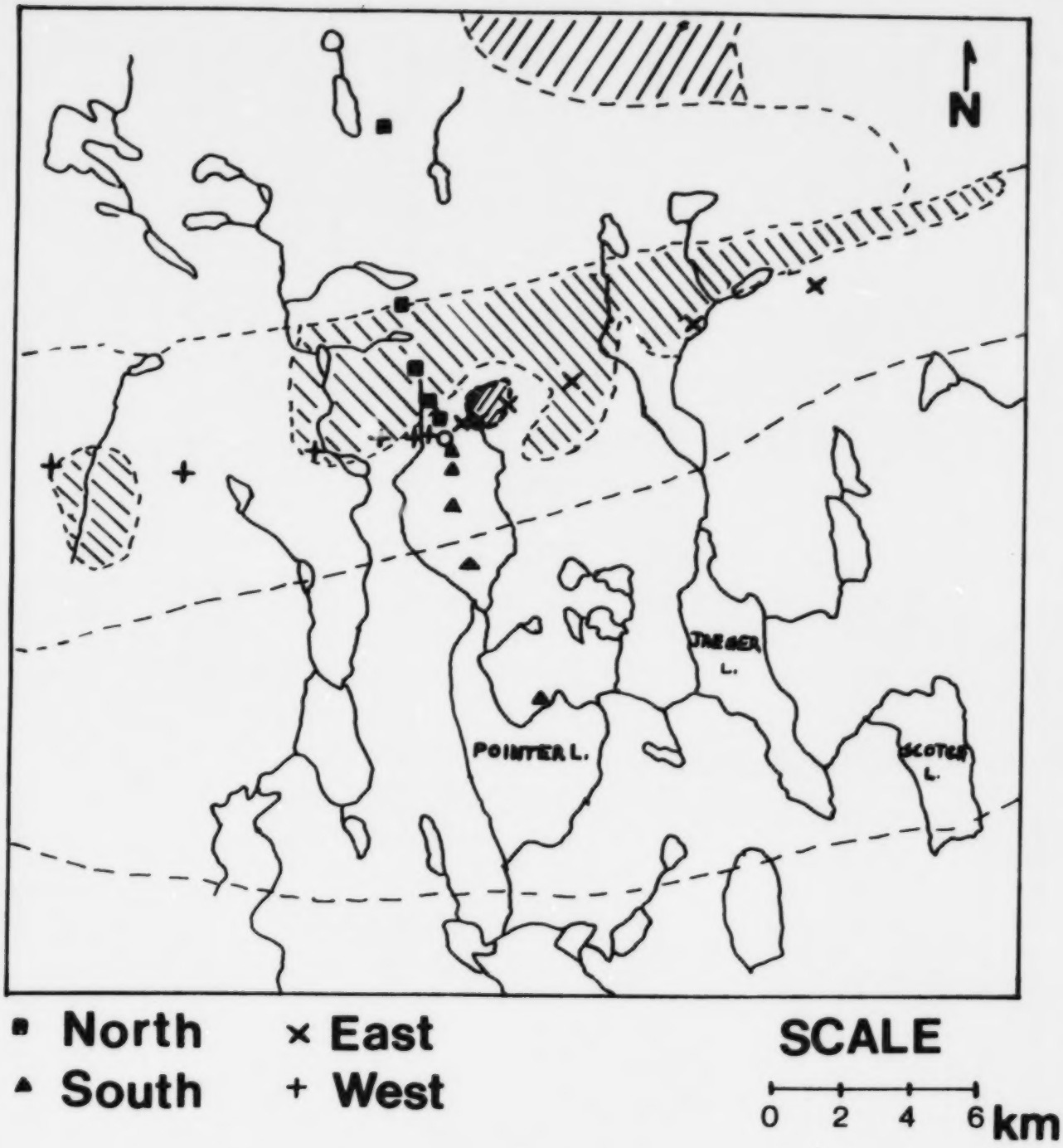

Figure 1. Area map indicating collection sites for the Lone Gull transcects. The hatched areas denote orthoquartzite (\\\\\\) and intrusive rock (//////) formations.

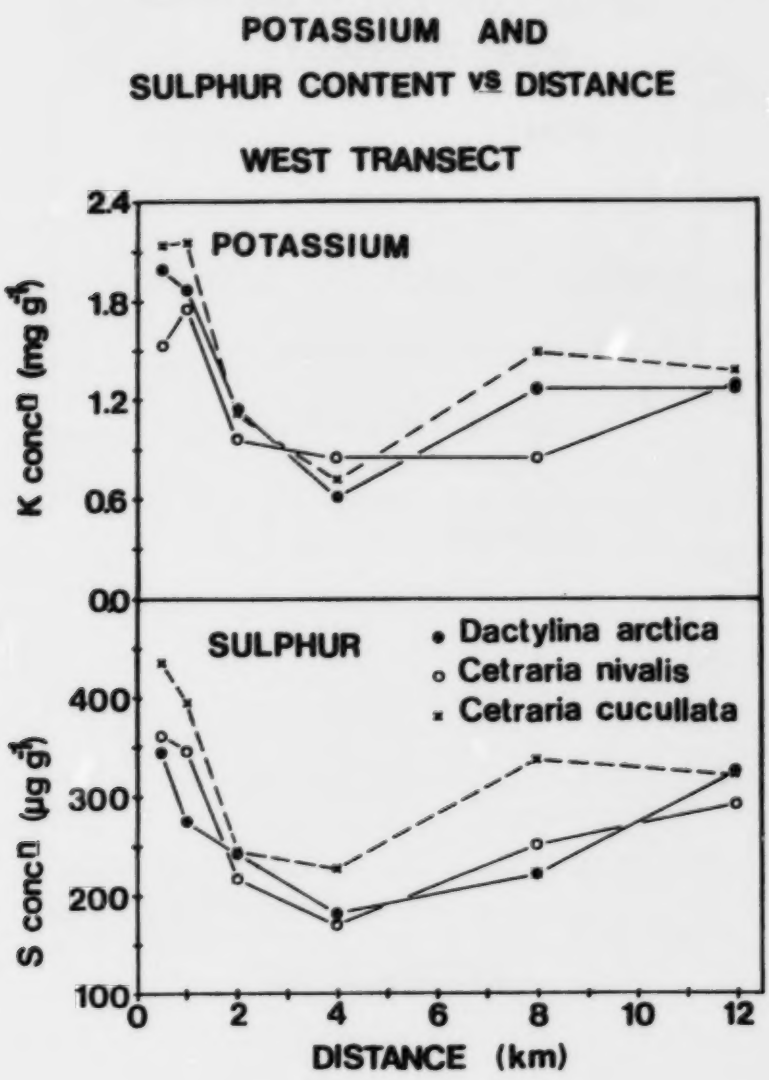

Figure 2. Potassium and sulphur concentrations in lichen samples collected along the West Transect originating at the Lone Gull field camp. The standard deviation (SD), based on background and peak counts, was typically $\pm$ 6 µg g^{-1} (S) and $\pm$ 0.03 mg g^{-1} (K), expressed per air-dry weight of lichen.

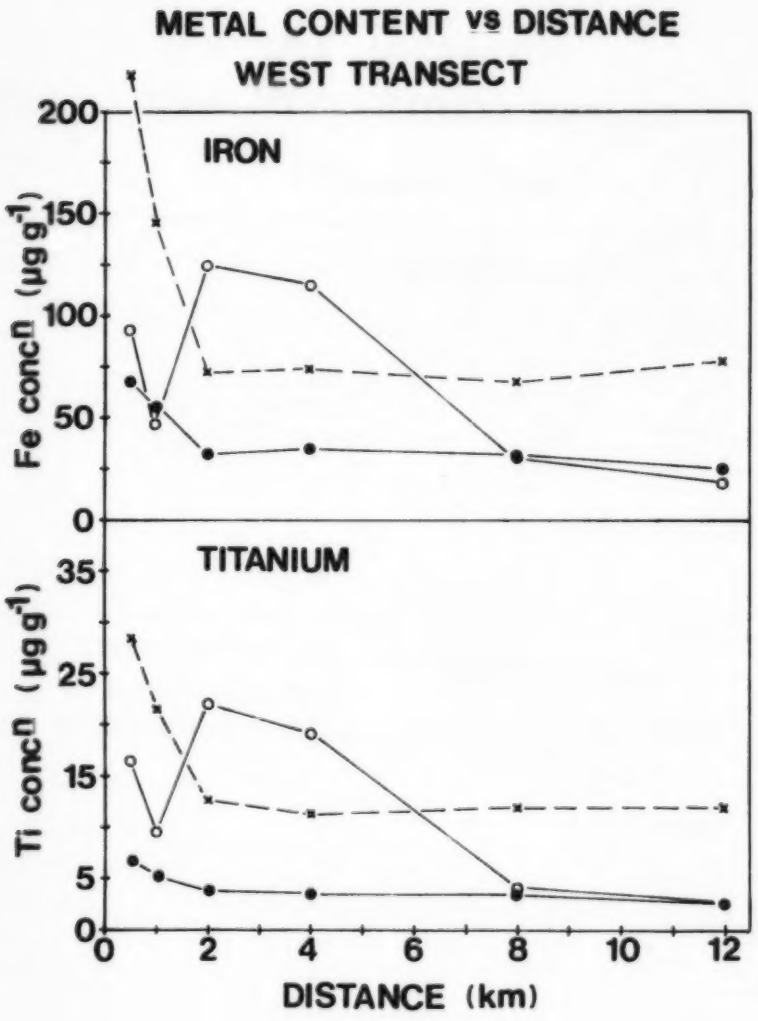

Figure 3. Iron and titanium concentrations in lichen samples collected along the West Transect; SD = ± 2 µg g^{-1} (Fe) and ± 0.4 µg g^{-1} (Ti). Species key as in Figure 2.

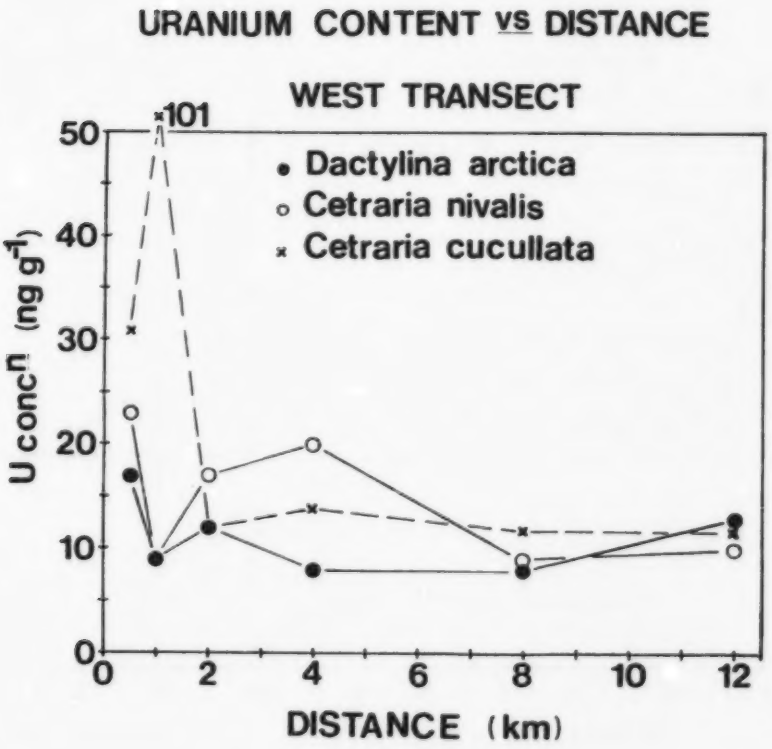

Figure 4. Uranium concentrations in lichen samples collected along the West Tansect; SD = $\pm$ 3 ng g^{-1}.

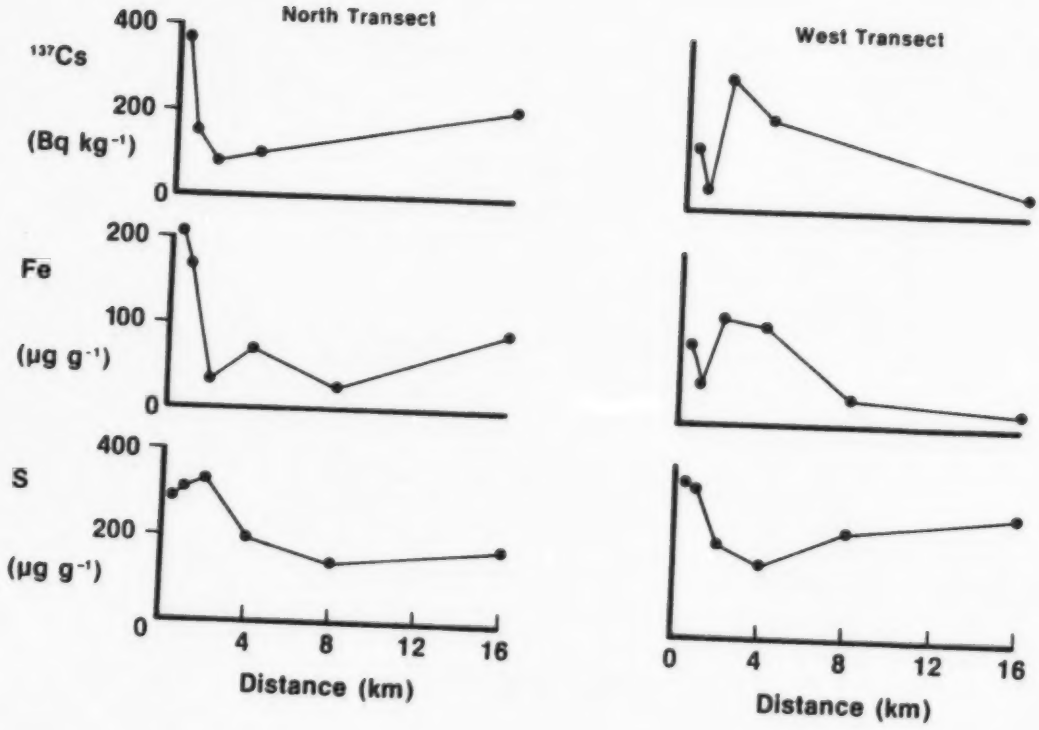

Figure 5. Iron, Sulphur and Cesium-137 concentrations in Cetraria nivalis collected along the North and West Transects; SD (^{137}Cs) = + 50 Bq kg^{-1}.

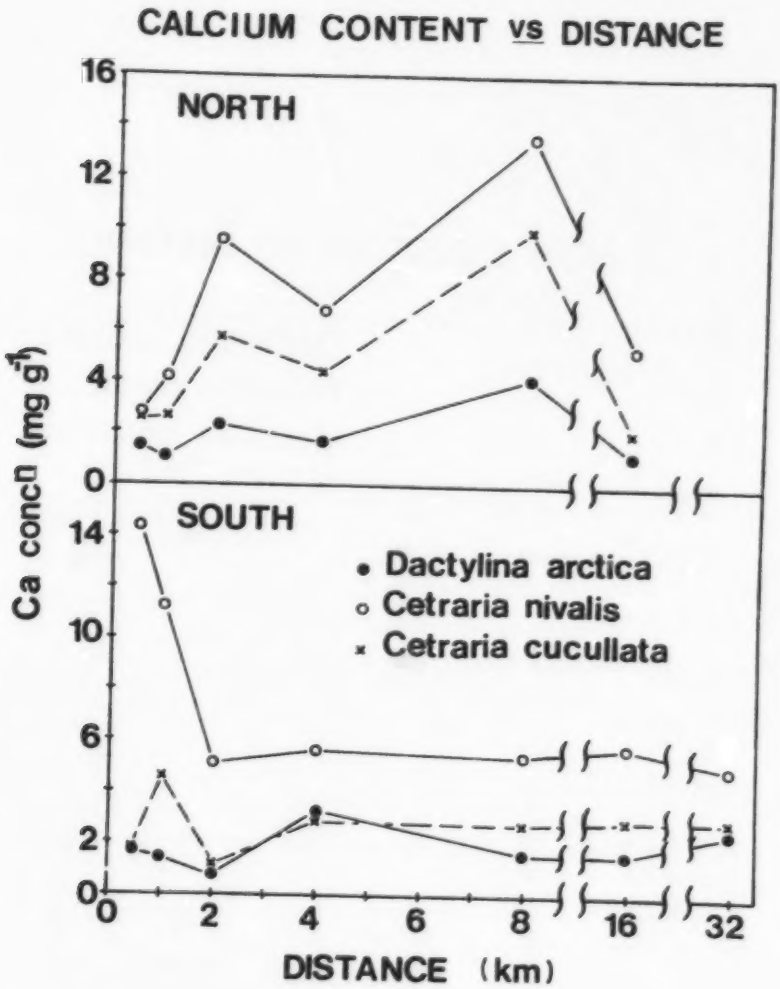

Figure 6. Calcium concentrations in lichen samples collected along the North and South Transects; SD = ± 1-2% of the contents shown.

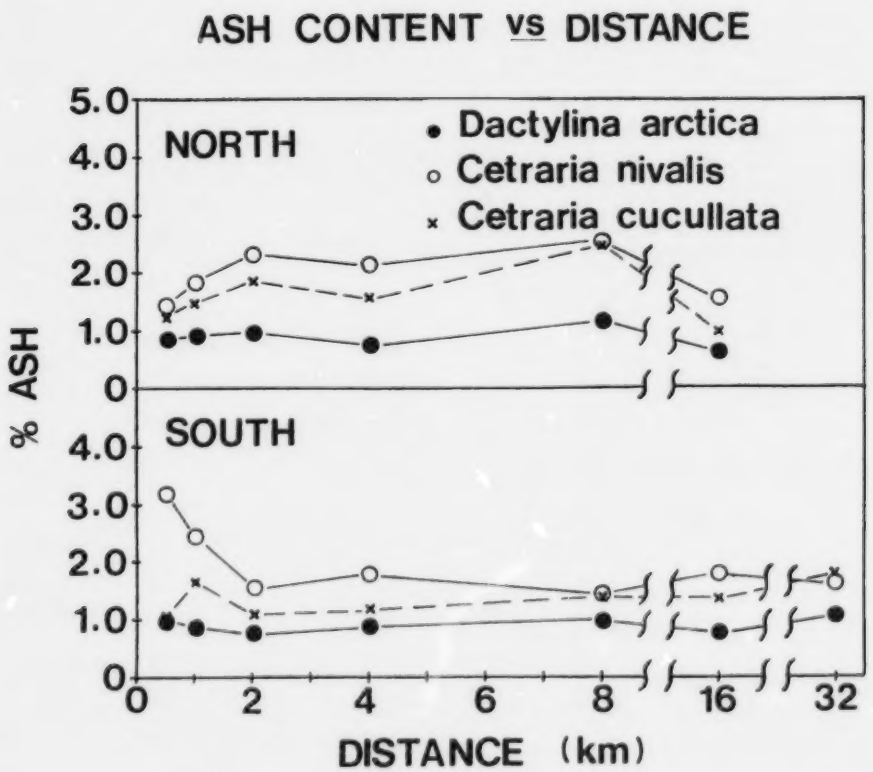

Figure 7. Percentage incombustible ash in lichen samples collected along the North and South Transects.

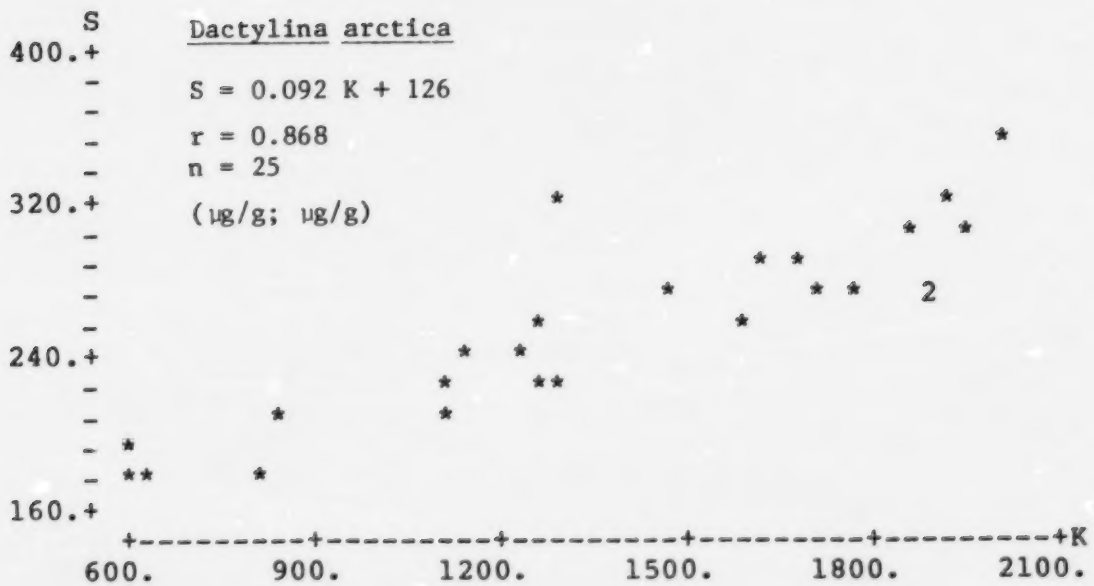

Figure 8. A scatter diagram showing the strong correlation between the sulphur and potassium concentrations in Dactylina arctica (all sites). The regression equation given does not imply a dependent/independent relationship between these variables. Also shown are the correlation coefficient (r), the number of points (n), and the units for each axis. Occurrence of a number in the scatter diagram indicates the number of coincident data points. A similar relationship also exists for the other two lichen species.

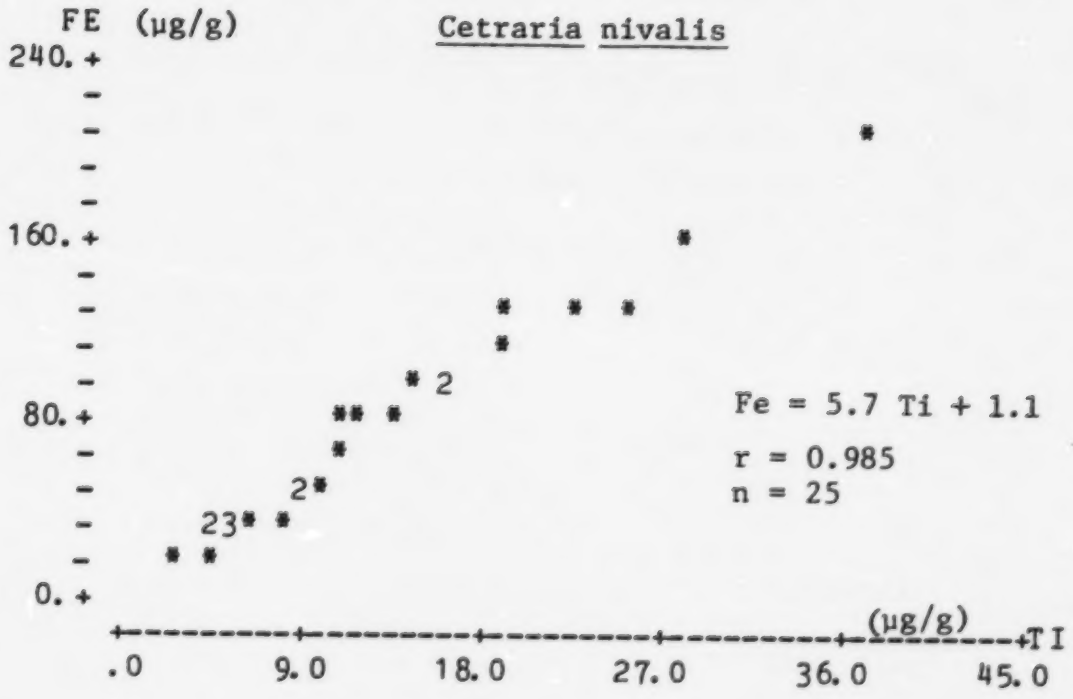

Figure 9. A scatter diagram showing the linear relationship between the iron and titanium concentrations in Cetraria nivalis for all sites; conventions as in Figure 8. The dependence observed may be attributed to the presence of iron and titanium in particulates trapped in lichen thalli (see text).

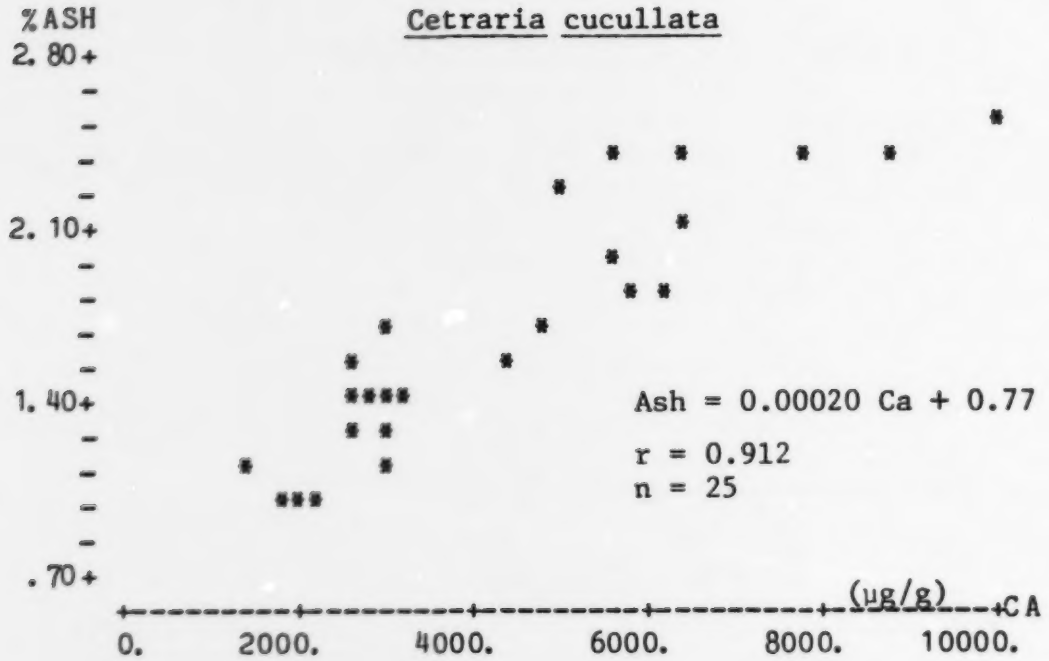

Figure 10. A scatter diagram showing the strong correlation between the percent ash content and the calcium concentrations of Cetraria cucullata for all sites; conventions as in Figure 8. Mass balance calculations suggest that calcium is the major independent variable contributing to the ash content.

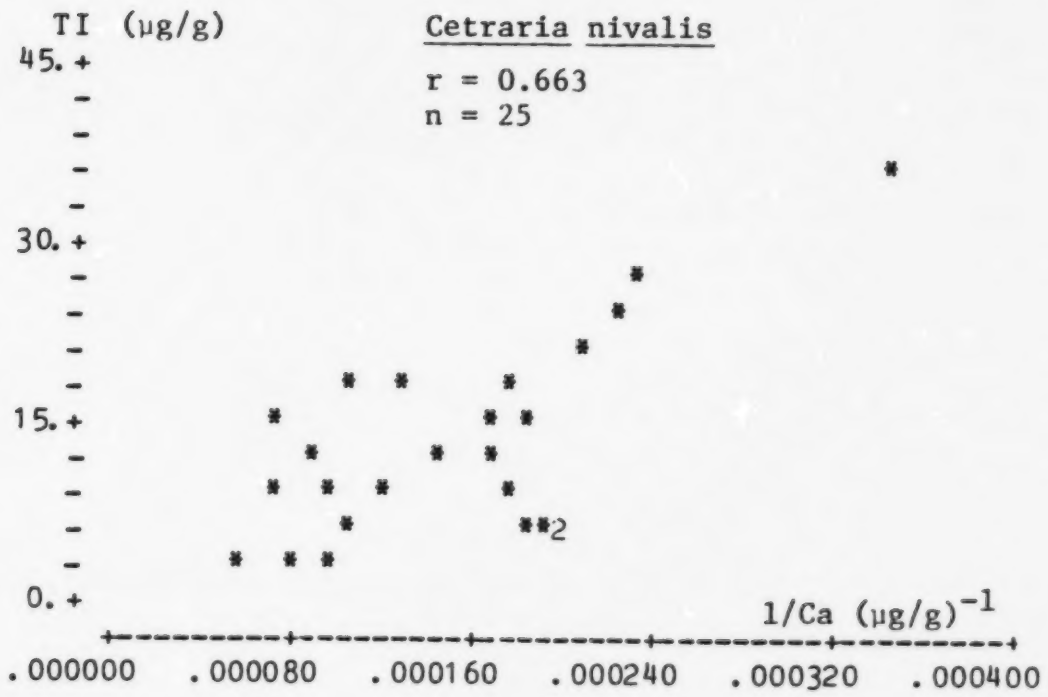

Figure 11. Observed relationship between the titanium content and the reciprocal of the calcium concentrations (all sites); conventions as in Figure 8. As explained in the text, the presence of calcium salts in the interstitial spaces of lichen thalli is suspected to exclude exogenous dust particles derived from rock and soil.

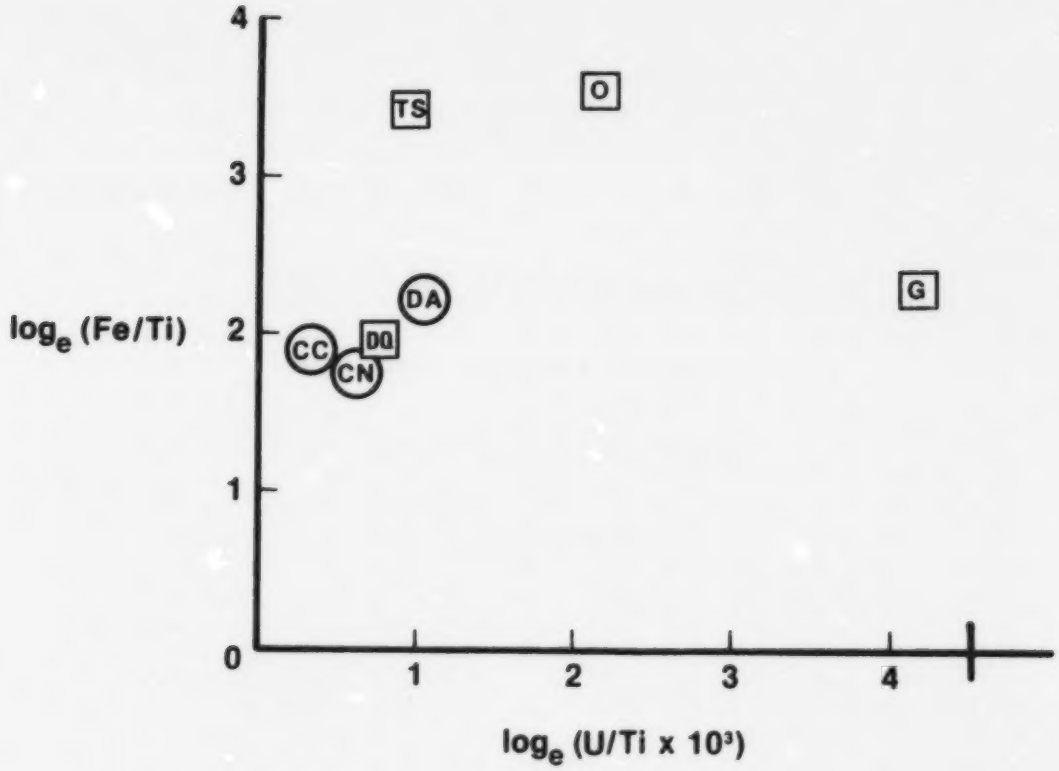

Figure 12. The Fe/Ti and U/Ti quotients for the lichens Cetraria cucullata (CC), C. nivalis (CN) and Dactylina arctica (DA). Also shown are the quotients for the rock types: dirty quartzite (DQ), thelon sandstone (TS), orthoquartzite (O) and granite (G). The grouping of the dirty quartzite with the lichens suggests that this rock type is the main source of the particulates trapped in lichens.

APPENDIX

ELEMENTAL CONTENT DATA FOR LICHENS COLLECTED AT LONE GULL CAMP NEAR BAKER LAKE, N.W.T., IN JULY, 1982.

APPENDIX : The elemental concentrations and % ash for Cetraria cucullata C. nivalis and Dactylina arctica for all collection sites. Values are given per dry weight in µg/g except for ash (%), Cs (nCi/kg) and distance (km). * = missing value

KEY : T = Transect , Sp = Species , D = Distance
Transect 1 = East , 2 = North , 3 = South , 4 = West
Species 1 = Cetraria cucullata
2 = Cetraria nivalis
3 = Dactylina arctica

T	Sp	D	Ash	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
1	1	0.5	2.44	8730	2.8	4.7	51.3	1500	1.8	3.7	321.3	8.3	0.018
1	1	1.0	2.15	6420	5.5	2.3	71.1	1680	1.6	3.2	362.0	11.5	0.025
1	1	2.0	1.21	2960	6.8	4.0	113.0	1740	2.7	4.9	327.5	16.3	0.024
1	1	4.0	1.79	6140	2.6	3.0	103.3	1350	3.5	6.6	262.8	16.5	0.016
1	1	8.0	2.33	5600	*	2.8	99.5	1220	1.2	3.3	309.8	17.0	0.011
1	1	12.0	0.94	1990	5.9	3.9	90.8	950	2.0	3.0	237.9	13.8	0.012
1	2	0.5	3.12	18600	7.0	1.6	19.0	1420	2.5	1.9	348.5	4.1	0.031
1	2	1.0	2.05	10200	0.9	1.2	41.5	1330	1.2	2.7	265.1	8.7	0.010
1	2	2.0	3.69	5840	3.3	2.3	75.9	1280	2.5	3.1	260.1	11.0	0.037
1	2	4.0	2.15	7720	9.3	3.4	128.8	750	5.9	5.7	120.5	19.2	0.029
1	2	8.0	1.65	4390	8.5	2.4	132.9	1240	1.6	5.5	285.4	25.4	0.026
1	2	12.0	1.73	5000	1.4	1.8	24.1	1000	0.9	2.4	166.7	4.6	0.010
1	3	0.5	1.31	3280	3.8	3.5	32.7	1760	1.4	8.4	265.2	3.9	0.030
1	3	1.0	0.98	2720	3.3	5.2	31.1	1470	1.8	4.8	276.4	3.1	0.012
1	3	2.0	0.71	1510	3.9	4.4	45.8	1220	1.4	2.2	241.1	6.3	0.013
1	3	4.0	0.61	1160	4.4	3.2	31.2	1290	1.0	4.1	222.8	4.2	0.011
1	3	8.0	0.83	1770	5.3	4.4	69.8	1260	1.6	7.1	250.5	7.5	0.010
1	3	12.0	0.63	1510	3.4	4.7	37.6	1120	1.7	11.1	209.2	3.6	0.011
2	1	0.5	1.24	2620	3.5	5.8	68.5	2000	2.9	5.7	353.5	10.2	0.016
2	1	1.0	1.48	2680	4.2	3.9	129.7	1980	1.8	4.2	339.9	19.0	0.014
2	1	2.0	1.87	5860	2.5	0.6	48.9	1700	1.2	2.1	337.8	8.3	0.000
2	1	4.0	1.51	4470	4.0	3.0	66.9	630	2.4	3.0	148.7	9.9	0.013
2	1	8.0	2.49	10000	*	0.6	60.1	640	1.9	4.0	207.0	10.3	0.015
2	1	16.0	0.97	2240	*	2.7	96.8	750	2.2	3.6	201.2	13.1	0.024
2	2	0.5	1.42	2930	10.0	3.1	206.1	1490	1.5	5.9	289.2	37.0	0.031
2	2	1.0	1.84	4250	4.2	3.3	167.7	1670	2.9	6.8	315.6	28.3	0.017
2	2	2.0	2.22	9750	2.3	2.3	33.9	1470	0.9	2.7	335.0	5.4	0.008
2	2	4.0	2.31	6970	2.8	0.7	70.9	780	0.9	4.0	196.8	10.9	0.020
2	2	8.0	2.55	13800	*	22.0	25.2	590	1.6	6.5	139.0	8.1	0.014
2	2	16.0	1.55	5420	5.7	3.0	92.5	660	3.3	9.1	176.4	15.9	0.015
2	3	0.5	0.84	1580	3.1	7.6	33.8	1930	1.2	4.5	322.1	3.8	0.012
2	3	1.0	0.90	1110	4.0	4.2	53.4	1900	1.5	4.8	277.6	6.6	0.019
2	3	2.0	0.96	2380	2.1	0.9	39.1	1620	2.0	2.0	281.4	5.0	0.010
2	3	4.0	0.73	1790	8.2	4.3	31.3	840	3.6	6.9	202.1	3.5	0.000
2	3	8.0	1.18	4220	0.0	1.8	25.4	610	1.0	3.0	199.3	2.9	0.006
2	3	16.0	0.63	1240	*	3.8	77.5	810	2.3	6.1	174.6	7.1	0.016

APPENDIX page 2

T	Sp	D	Ash	Ca	Cs	Cu	Fe	K	Ni	Pb	S	Ti	U
3	1	0.5	1.01	1820	7.8	2.8	101.5	1870	2.2	2.9	324.2	15.9	0.017
3	1	1.0	1.67	4750	5.1	1.1	67.1	1700	2.2	6.1	332.7	10.5	0.017
3	1	2.0	1.07	1310	5.2	2.2	71.6	1870	1.2	5.2	302.2	10.9	0.020
3	1	4.0	1.18	2900	2.3	2.5	86.9	900	2.2	3.8	220.4	13.6	0.016
3	1	8.0	1.33	2860	*	5.1	75.3	1640	4.6	4.3	354.6	10.4	0.018
3	1	16.0	1.34	2960	*	1.0	77.7	1370	2.1	3.6	260.0	10.5	0.014
3	1	32.0	1.70	2930	*	1.4	82.7	1790	1.4	1.7	379.4	12.7	0.017
3	2	0.5	3.18	14500	6.9	3.2	86.6	1380	3.0	13.2	333.9	13.7	0.031
3	2	1.0	2.42	11400	6.9	0.8	79.6	1530	1.3	3.1	341.4	11.4	0.034
3	2	2.0	1.51	5230	2.4	0.0	24.4	1830	1.4	1.1	323.0	5.0	0.000
3	2	4.0	1.77	5760	5.4	2.3	51.8	1120	1.2	5.6	198.4	8.9	0.024
3	2	8.0	1.43	5510	*	2.4	35.9	1000	2.4	4.2	213.8	6.2	0.012
3	2	16.0	1.80	5860	7.0	4.2	88.9	1660	1.5	5.1	295.1	14.5	0.018
3	2	32.0	1.57	5080	*	1.0	32.2	1660	0.8	1.7	319.5	5.1	0.010
3	3	0.5	0.99	1760	6.5	3.3	54.6	1720	1.7	7.8	269.3	5.1	0.014
3	3	1.0	0.85	1550	2.5	5.3	30.0	1860	1.5	5.3	307.4	3.5	0.011
3	3	2.0	0.77	840	4.0	1.3	40.9	1950	1.3	6.2	304.8	4.4	0.015
3	3	4.0	0.86	3280	4.7	5.7	27.9	610	2.2	5.9	182.8	3.3	0.011
3	3	8.0	0.95	1670	*	3.9	53.1	1580	2.0	3.8	254.2	6.7	0.018
3	3	16.0	0.79	1640	*	1.8	38.4	1120	1.4	3.1	223.8	4.3	0.011
3	3	32.0	1.09	2570	*	3.1	33.4	1680	3.1	8.3	281.3	3.5	0.012
4	1	0.5	2.21	4910	4.8	4.6	219.3	2150	1.7	3.6	436.5	28.5	0.031
4	1	1.0	1.41	2500	4.9	6.8	146.4	2170	1.4	2.6	397.3	21.6	0.101
4	1	2.0	1.99	5600	2.1	3.1	73.5	1140	2.0	2.9	245.9	12.8	0.012
4	1	4.0	2.37	7780	3.6	3.3	74.9	730	1.3	2.6	229.6	11.4	0.014
4	1	8.0	1.39	3130	*	2.5	67.9	1500	1.3	1.2	333.4	12.0	0.012
4	1	12.0	2.37	6320	*	2.6	78.4	1400	1.0	6.1	324.5	12.2	0.012
4	2	0.5	1.98	9620	3.9	2.9	93.8	1540	1.6	3.2	363.3	16.5	0.023
4	2	1.0	1.87	8590	1.5	3.0	47.3	1760	1.3	2.1	348.1	9.6	0.000
4	2	2.0	1.37	4750	8.5	1.6	125.1	960	1.1	9.2	219.4	22.2	0.017
4	2	4.0	1.53	5580	5.8	1.6	115.6	860	1.3	4.4	171.1	19.2	0.020
4	2	8.0	2.25	10200	*	1.8	31.9	860	2.2	1.8	251.3	4.4	0.008
4	2	12.0	2.65	12300	1.3	1.0	19.3	1300	1.0	1.2	293.2	2.9	0.010
4	3	0.5	1.18	3240	4.0	4.0	67.7	2000	1.9	4.7	346.6	6.8	0.017
4	3	1.0	0.85	1300	4.1	4.8	56.2	1880	1.5	3.0	276.3	5.3	0.009
4	3	2.0	0.78	2300	1.4	2.5	33.8	1150	1.0	3.0	243.4	3.9	0.012
4	3	4.0	0.87	3040	*	5.1	35.6	620	1.3	15.5	183.2	3.9	0.008
4	3	8.0	0.84	2140	*	4.9	32.3	1270	1.2	4.8	222.9	3.8	0.008
4	3	12.0	1.03	2910	2.2	3.2	25.8	1290	1.1	1.7	327.5	2.9	0.020